DISTRIBUTED AIR/GROUND TRAFFIC MANAGEMENT SIMULATION: RESULTS, PROGRESS AND PLANS

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ABSTRACT

A mixed-fidelity simulation environment for human-in-the-loop study of Distributed Air / Ground – Traffic Management (DAG-TM) concepts has been developed at NASA's Ames Research Center. The simulation environment facilitates large-scale experiments supporting high numbers of pilot, air traffic controller, and air traffic manager participants. Decision Support Tools (DST) for flight crews and air traffic service providers are accessible at the respective operator stations. Many operator positions can be augmented or autonomously run with agent support.

We present samplings of results from studies conducted using this environment, and outline our goals in terms of improving and refining the simulation. We review the overall simulation architecture, and the key upgrades, including:

- Converting controller and desktop simulator displays to run Multi Aircraft Control System (MACS) interfaces. Developed at Ames, MACS stations are user configurable for the specific participant - Center controller, TRACON controller, traffic flow manager, or pilot.
- Upgrading the older Center TRACON Automation System (CTAS) based generic controller *radar displays* with MACS embedded high fidelity replicas of fielded Center and TRACON controller stations.
- Replacing the conventional analog voice communication system with a digital, voice-over-Internet Protocol system permitting many more users – participants and simulation support personal – to communicate simultaneously, over multiple channels.
- Incorporating a weather server to provide simulated, real-time winds and weather events.

Work is underway to connect the NASA Ames-based simulation to the Air Traffic Operations Simulator at NASA Langley in order to conduct studies of air traffic operational concepts, distributed across the two NASA Centers.

The Advanced Air Transportation Technologies (AATT) project office of NASA's Airspace Systems Program provides funding for this work.

INTRODUCTION

Revolutionary air traffic operational concepts need to be studied in depth before informed recommendations about practical implementation can be made. The complexity and highly dynamic nature of real-time interactions between airline dispatchers, flight crews, and air traffic service providers warrants a comprehensive simulation of all aspects to determine concept feasibility. Agent-based environments such as Monte Carlo type fast time studies can provide invaluable insights into potential benefits, safety implications and the stability of a complex system. However, it is necessary to have human players interact with a novel concept in an operationally viable environment. Therefore, researchers at NASA's Ames and Langley Research Centers are developing a versatile simulation environment that enables full-scale, end-to-end human-in-the-loop (HITL) investigation of advanced concepts for NAS air traffic operations. The Ames and Langley based simulation environments have already been partially connected, leading up to an even larger-scale distributed test bed. This paper focuses on the capabilities developed and used in the human factors division at NASA Ames Research Center.

The base simulation architecture and capabilities were initially described in Prevot et al. (2002)[1]. We will first briefly re-visit this capability, which was used in September 2002 to conduct DAG-TM experiments[2,3,4,5]. Example results obtained during these experiments will be presented illustrating the effectiveness of the simulation environment. Following this we describe the next evolutionary step that will enhance the fidelity of many components. These new components are currently being phased in and will completely replace the original components by September 2003. Finally, we will outline how the Ames' simulation will be connected to the Langley simulation laboratory, and which additional components are expected to be on-line by early 2004.

2002 Simulation Environment

Figure 1 shows the NASA Ames DAG-TM simulation infrastructure[1] used in 2002 through early 2003. The main NASA Ames facilities are:

1. Airspace Operations Lab (AOL), providing aircraft target generation, Air Traffic Control and Management stations augmented with CTAS[6], decision support tools, MACS[7] pilot stations, additional CDTI stations, and experiment control and management facilities.
2. Flight Deck Display Research Lab, providing mid-fidelity desktop simulators equipped with Cockpit Displays of Traffic Information CDTI[8,9]
3. Crew Vehicle Systems Research Facility (CVSRF), providing high fidelity full mission flight simulators.

The AOL controls the overall scenario progress, hosts the Air Traffic Control and Management facilities, and pilots the majority of the aircraft in the scenarios. The research in the AOL focuses on the human factors of ground ATC/ATM operations and decision support tool integration. Other facilities participate in the same traffic environment. The full mission simulators at the CVSRF provide the high fidelity environment for realistic flight deck operations research. The Flight Deck Display Research Lab addresses the in depth research, development, design and testing of flight deck-based situational displays, and can

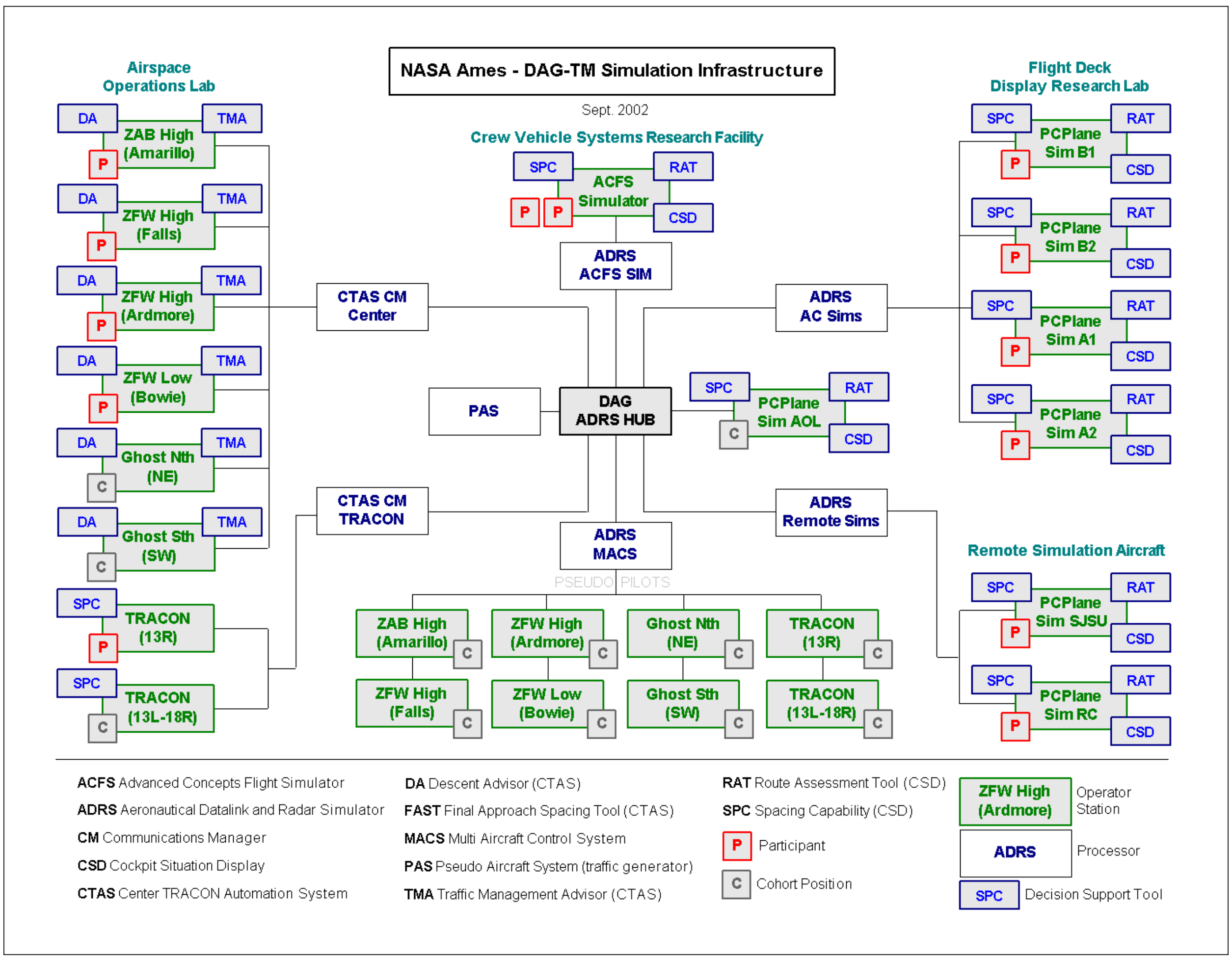

Figure 1. DAG-TM simulation environment used during September 2002 experiments

evaluate advanced concepts before integrating them into a full mission flight simulator.

Each of these facilities can also run subsets or multiple instances of subsets of the simulation independently. The different simulation subsets are simply integrated by connecting the ADRS (Aeronautical Data link and Radar Simulator) hubs to each other. In addition to these currently used on-site facilities other Ames-based and off-site facilities can be connected to the same simulation as explained in detail in Prevot et al[1]. In the next section we present some data samples that were gathered in this test bed during DAG-TM simulations in 2002.

SEPTEMBER 2002 SIMULATION

EXPERIMENT OVERVIEW

The simulation capability described above was used in September 2002 to run an experiment testing three DAG-TM concepts. A complex arrival traffic problem involving roughly 90 aircraft (half arrivals, half departures or overflights) was simulated spanning five Center and TRACON sector positions. A total of 24 individuals actively participated in each 75 minute run, including:

- 2 airline pilot subjects flying the ACFS full mission simulator
- 6 airline pilot subjects flying CDTI-equipped desktop simulators in distributed locations
- 8 "pseudopilots" flying the remaining 80+ aircraft from MACS workstations in the AOL
- 5 full performance level controller subjects working sector positions in the AOL
- 3 retired controllers controlling traffic flowing into and out of the problem (also in the AOL)

Detailed research results are presented in Prevot et al. (2003)[4] and Lee et al. (2003)[5]. A sample of the results from this experiment is provided below to illustrate the type of data that can be collected in this simulation environment.

Controller and ATM Perspective

One objective of the experiments was to measure the impact of novel en route DAG-TM concepts on providing an efficient feed of aircraft arrivals into terminal areas during rush periods. A limiting factor in arrival capacity is aircraft delivery accuracy. Arrival capacity can be increased if all available "slots" are utilized and all scheduled aircraft are delivered to approach control on time.

Two experimental en route DAG-TM conditions labeled concept element (CE) 5 ("free maneuvering") and CE 6 ("trajectory negotiation") were simulated as well as a current day control condition labeled "baseline". In the experimental conditions aircraft were expected to be delivered more accurately than in the control condition. One measure for this aspect is the difference between scheduled time of arrival (STA) and actual time of arrival (ATA) at the meter fix.

Figure 2 show histograms combining all arrival aircraft from all runs for each experimental condition. It shows the flow from the controllers' perspective.

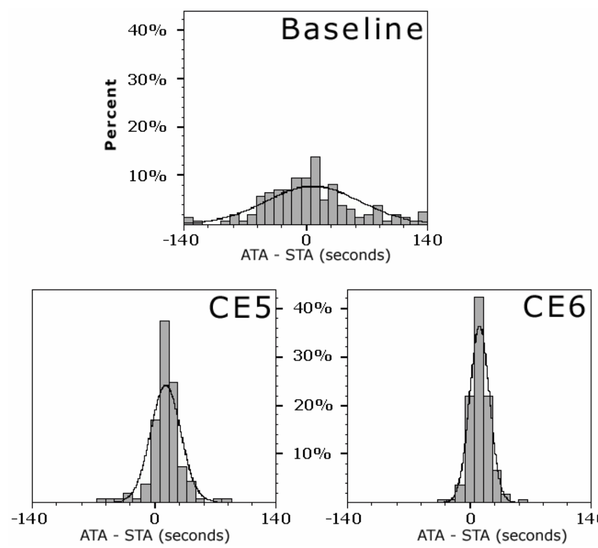

Figure 2. Arrival Accuracy (ATA –STA)

Arrival accuracy varied significantly more under the baseline condition (SD = 53.9) than either CE 6 (SD = 11.4) or CE 5 (SD = 17.2), suggesting that more aircraft were delivered on time using DAG-TM arrival metering than in current day operations.

Pilot Perspective

Figure 3 shows similar data from the pilot perspective, depicting how well the participant pilot aircraft crossed the metering fix within the target +/- 15 seconds, in absolute terms, as compared to the baseline condition. Figure 2 combines all aircraft including those operated by confederate pseudo pilots through MACS multi aircraft pilot stations. Figure 3 represents the subset of aircraft operated by subject pilots. This analysis can be used to determine for example whether the confederate pilot performance is equivalent to the participant pilot performance from an air traffic control standpoint.

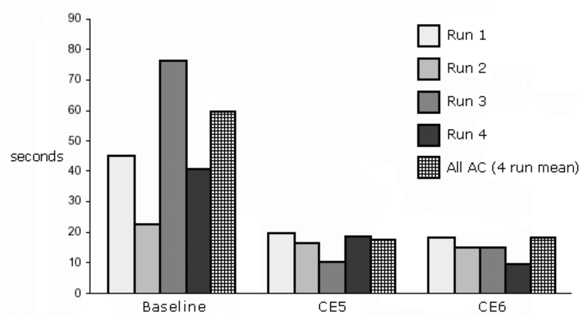

Figure 3. Absolute meter fix crossing deviation: participant aircraft (versus the all-aircraft average across 4 runs)

CONTROLLER WORKLOAD

The controller workload was measured using post-run ratings of mental demand, effort, frustration, and performance. The main workload impact was seen at the low altitude sector (Bowie) that benefits most from the trajectory-based approach in CE 5 and CE 6, because the feeding high altitude sectors (Falls and Ardmore) set up the trajectories for the downstream sector (Bowie) (see Figure 4). The low altitude sector controller reported less mental demand, effort, and frustration and achieved a higher level of performance while the feeding high altitude sector controllers gave similar workload ratings across conditions.

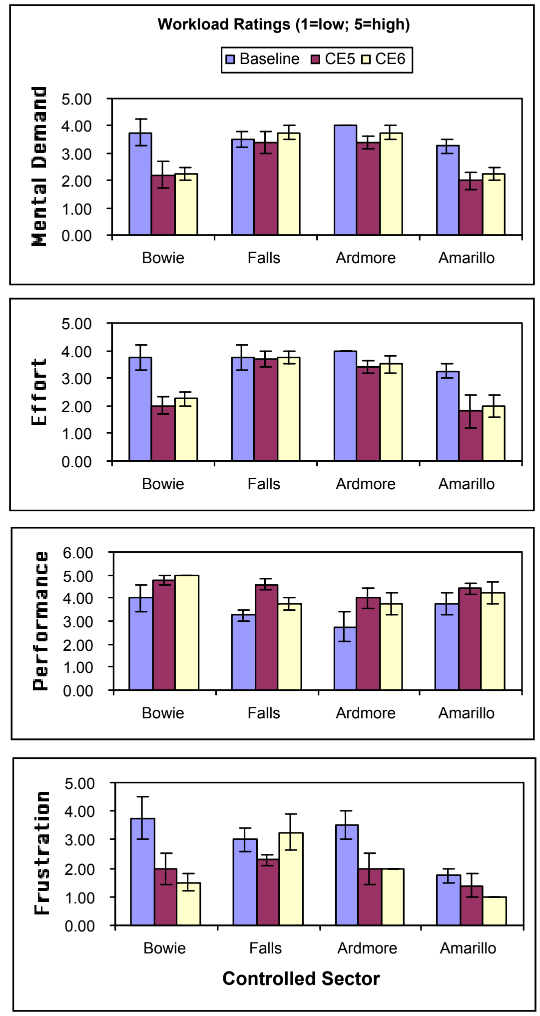

Figure 4: Controller Workload

The examples above indicate that the simulation provides a test bed for investigating all aspects of DAG-TM, ranging from global efficiency and safety concerns, like traffic flow management and separation violations to individual controller and pilot human factors aspects, like workload or human computer interface considerations.

2003 SIMULATION ENVIRONMENT

Despite the demonstrated power of the simulation environment, we identified the need for improvements in several areas. These include:

- Generic controller interfaces
- Number of pro-active pilots
- Voice communication system
- Real-time weather feed

Each of these issues is addressed below and the respective improvement is presented. At the end of this section the resulting new simulation environment is presented and described.

CONTROLLER INTERFACES

Over the past five years the CTAS embedded plan-view graphical user interfaces (PGUI) were used as the primary controller interface. These interfaces are well suited for traffic visualization and demonstration purposes but differ significantly from fielded interfaces. Air traffic controllers are not familiar with the basic human-computer interaction paradigm and therefore require extensive training to use the system, even for otherwise unchallenging tasks. This results in increased training time as well as unwanted

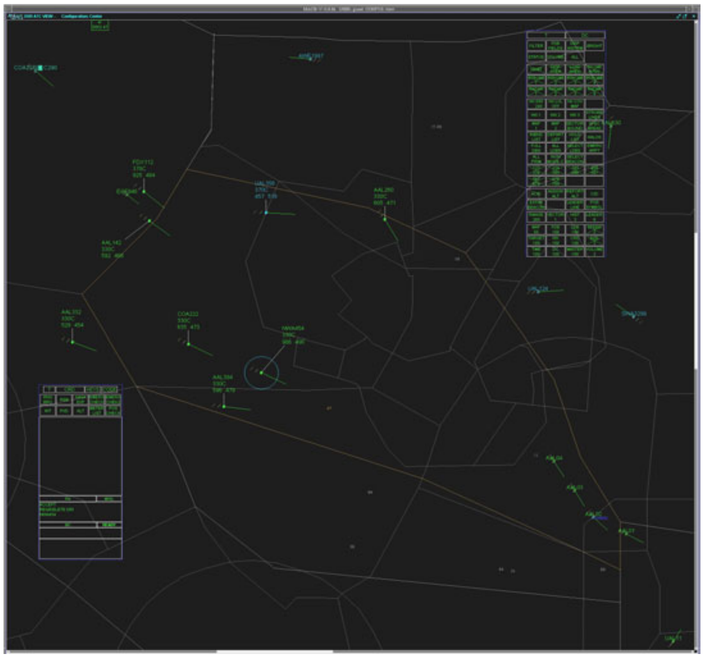

Figure 5. MACS DSR Center Controller Display

caveats to obtained experimental data due to unfamiliarity effects and resulting errors.

Obtaining and integrating the 'real' controller interfaces into the simulation environment would, however, have reduced the rapid prototyping capabilities that are invaluable for conducting research on advanced concepts. Therefore, mock-ups of actual Center and TRACON controller interfaces have been implemented as part of the Multi Aircraft Control System (MACS)[9]. These displays combined with the actual entry devices (keyboard, trackball) are intended to provide a familiar Look & Feel (L&F) to controllers. Thus, controllers need to be trained only on (minor) differences and new DSTs; and some of the unknowns from the experimental data are removed. Figures 5 and 6 depict examples of the MACS Center and TRACON controller interfaces.

The MACS embedded Center controller stations are replicas of the display system replacement (DSR) interfaces used in many Air Traffic Control Centers in the NAS. All standard DSR functions are supported like predictor lines, range rings, data tag positioning, flight data entries into the (simulated) host computer etc. Conflict Alert and Auto Handoff functions are emulated. DSR keyboards and trackballs have been obtained and can be used for data entry.

To provide TRACON controllers with a realistic environment a standard terminal automation replacement system (STARS) replica has been emulated in MACS. Data entries can be done via a STARS keyboard and trackball as well as standard computer keyboards and trackballs.

In addition to the basic DSR and STARS capabilities the MACS replicas are used as an environment for rapidly prototyping new capabilities. Data tags can be configured independently of the standard tags, e.g. for display of autonomous aircraft or to expand and show additional information when the controller dwells on an aircraft. Information like schedules and advisories generated by ATM/ATC decision support systems like the CTAS tools, TMA, D2, EDA, and FAST can be fed into the MACS stations via the simulation network and displayed on the controller displays.

When algorithms for novel research functionality are integrated into MACS, the visual and data entry support to access these functions can be prototyped on the respective controller displays. Thus, researchers can demonstrate a realistic prototype of new interfaces to the operational community early in the design process.

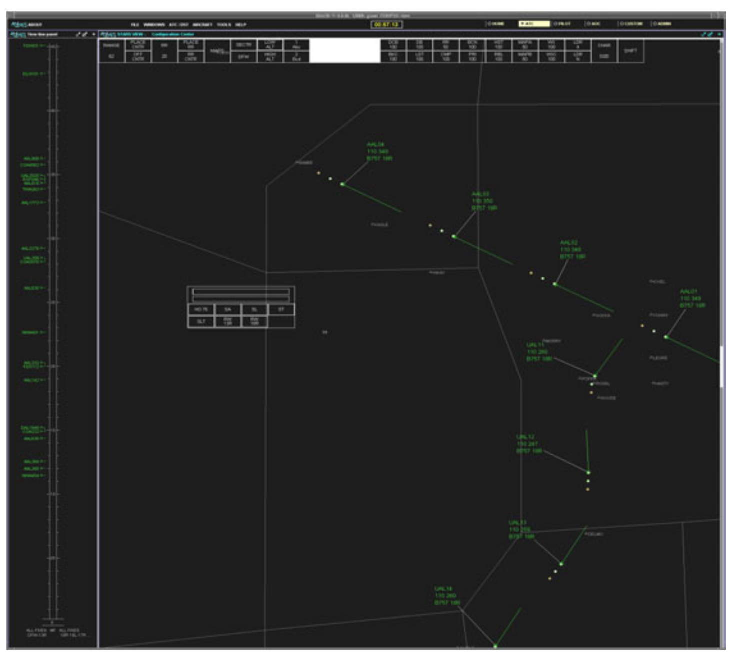

Figure 6. MACS STARS TRACON Controller Display

Number of Pro-Active Flight Crews

DAG-TM concepts increase the role of flight crews beyond responding to air traffic service provided clearances. Pilots are expected to play an active role in trajectory negotiation or separation tasks. The study of air traffic environments in which many flight crews act in this pro-active fashion puts additional challenges on the distributed simulation environment. In addition to including a large number of single aircraft CDTI-equipped pilot stations new multi aircraft CDTI-equipped pilot stations are under development. Examples for both types of stations are given in figures 7 and 8.

Figure 7 shows a possible single pilot station melding MACS and CDTI elements to simulate the typical pilot actions when interacting with the aircraft flight management system (FMS) or mode control panel (MCP). Therefore, a control and display unit (CDU) and MCP are provided that require the operator to perform all interactions similar to the real cockpit. These stations can be used to look at flight crew human factors in a mid-fidelity simulator.

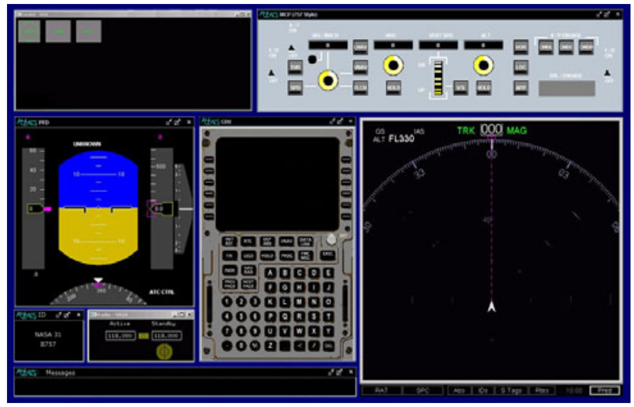

Figure 7. A possible melding of MACS and CDTI elements will form the new single aircraft participant pilot desktop simulator station.

Multi aircraft stations combine an extended agent support imbedded in MACS and the advanced conflict detection and resolution capabilities of the CDTI in one station. The MACS agent support can direct the pilots' attention towards an upcoming conflict or weather situation on one of the aircraft he or she controls. Once aware of the problem the pilot can select this aircraft to resolve the issue using the CDTI.

In the example in figure 8 a pilot controls six aircraft that are shown in the aircraft list in the upper left corner. In contrast to the single pilot station shown in figure 7, this station is configured with "quick entry" panels for MCP and FMS values like cruise descent speeds, next waypoints, or complete standard routings.

A pilot can modify necessary parameters quickly and move on to the next aircraft. To other simulation participants all aircraft controlled by this station will behave like single piloted participant aircraft, while in fact they are operated by one (confederate) pilot with agent and CDTI support.

Figure 8. Example MACS station equipped with CDTI and agent support controlling several (here 6) aircraft

Voice

COMMUNICATION SYSTEM

The analog voice communication system used in previous experiments provides for a total of 14 operator stations, four of which can be accessed via telephone lines, e.g. from full mission simulators. Given the previous considerations it is desirable to have many more operators communicating in the same simulation run. Therefore a Voice over Internet Protocol (VoIP) system has been developed and integrated at NASA Ames.

Figure 9 shows a simplified diagram of the voice communication system. The DagVoice (Figure 10) and the PilotVoice (Figure 11) applications can be deployed on controller and pilot stations across laboratories and across research facilities as long as those stations have access to an internet connection. The voice system supports 14 voice channels. Each channel represents a unique frequency, hosted by a multicast voice server running on a dedicated host in the Flight Deck Display Research Lab at Ames. Up to 50 speakers overall can be accommodated across all channels without significant performance impact.

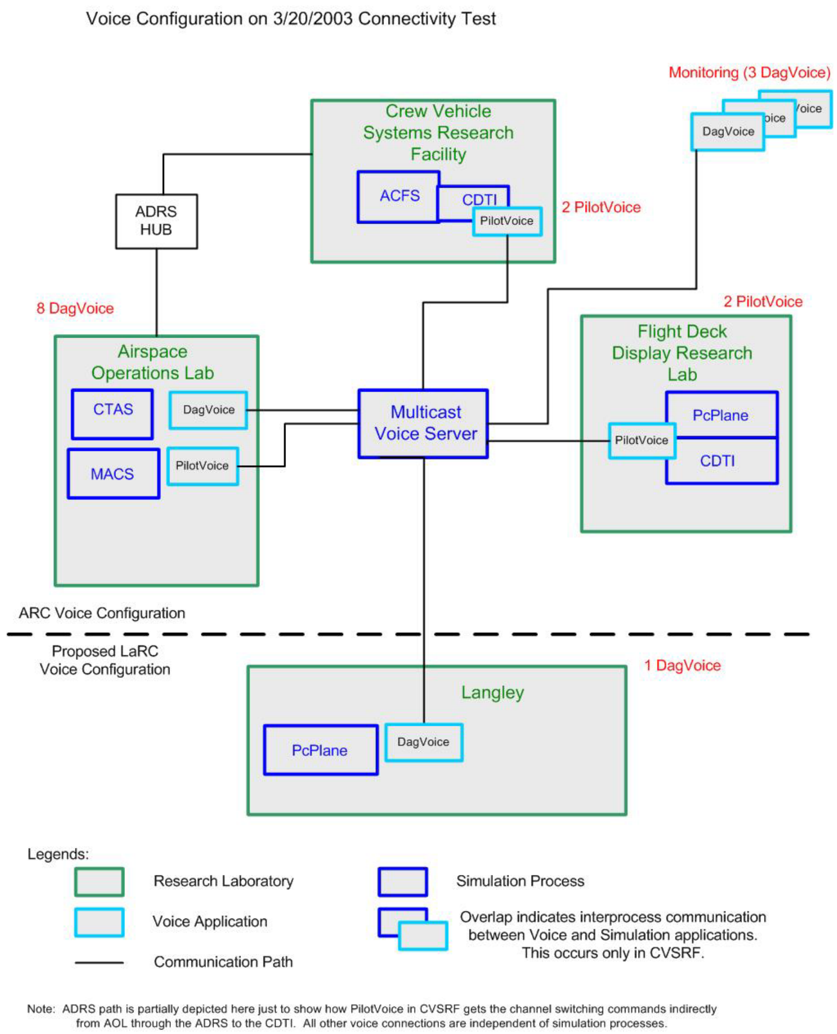

Figure 9. Voice communication system (VoIP)

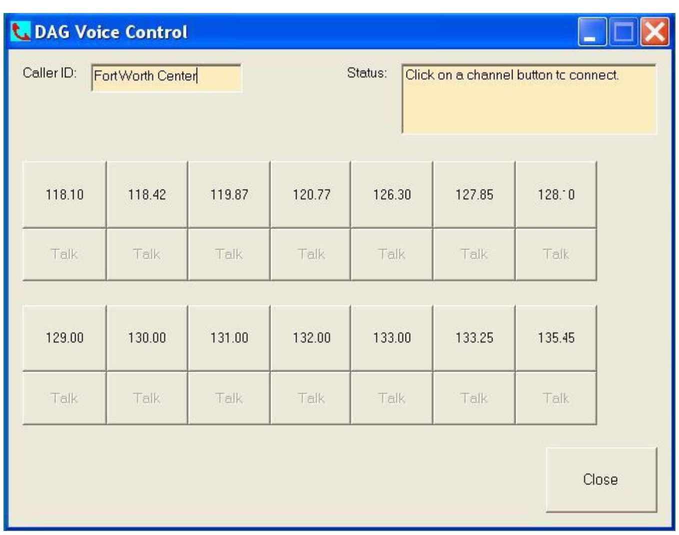

Figure 10. DagVoice controller frequency selection panel

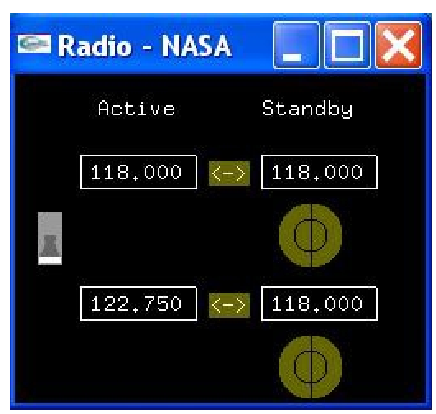

Figure 11. PilotVoice flight deck frequency selection panel

WEATHER SIMULATION

In previous DAG-TM experiments at NASA Ames atmospheric data were preloaded as files into all simulation components and remained unchanged throughout each experimental run. Localized weather cells were not included into the initial simulations. Testing the feasibility of DAG-TM concepts requires simulating operations under all weather conditions. Therefore, a weather server is added to the simulation environment.

The Thor Weather Scenario Server (named after Thor, the Norse god of thunder) is a data server designed to provide weather data to flight decks– with and without out-the-window- visual scenes, ground ATC, and other application requiring access to time-varying, real-world weather.[10] Thor is one component of a complete weather data delivery architecture, as shown in Figure 12.

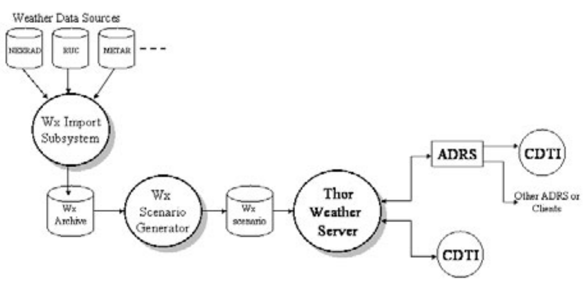

Figure 12. Weather Delivery Architecture

The data that Thor provides comes from *weather scenarios* that are generated in a separate application. These weather scenarios are based on prerecorded actual weather feeds of atmospheric conditions and convective weather cells of particular interest. The data can be gathered in the airspace that will be used during simulations or other areas and be converted to the simulation airspace. All necessary conversions are performed off-line.

Thor is a single process that extracts weather data from a scenario file and sends it in messages to clients (ADRS, CDTI) via a socket interface. Thor uses a configuration file for startup parameters (such as the scenario file name, its port number, etc.). It logs informational, debug and error messages to a log file. Figure 13 illustrates the context in which Thor operates.

When Thor starts up, it reads a configuration file that tells it (among other things) which scenario to load, loads the scenario, and then waits to be commanded to start the scenario. Once started, the Thor server uses an internal timer and the update rates in the weather scenario file to determine when a weather product should be updated. When a product needs to be updated, the Thor server will send a Notification message to any clients that have subscribed to update notifications for that product.

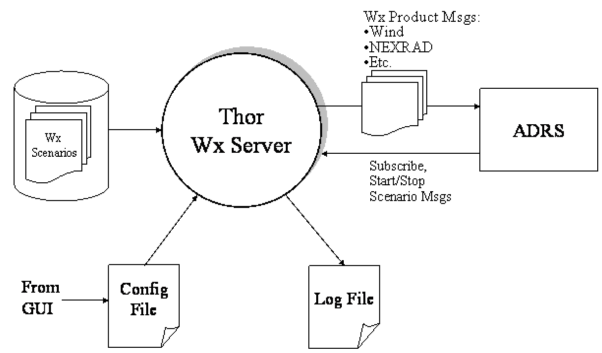

Figure 13. Thor Context Diagram

Upon receipt of an Update Notification message, a client may request the weather data from the Thor server or read the updated data directly from a local copy of the scenario file; in this case, the server is used solely as a sequencer.

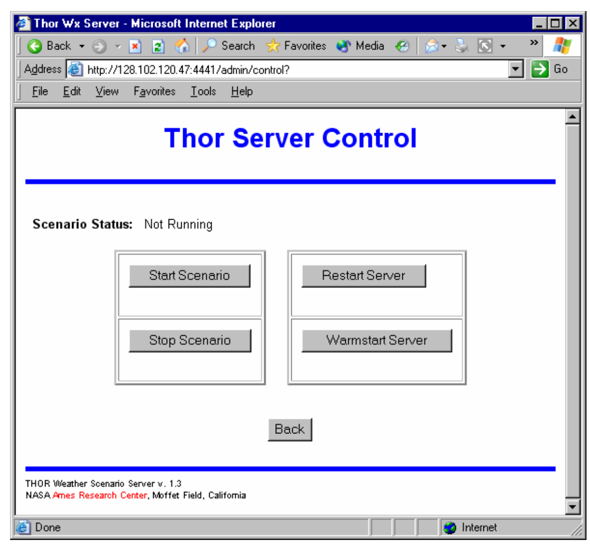

Figure 14. Thor server control page

The weather server can be configured and started via scenario management messages or a user interface accessible through an Internet browser. One of the pages provided for manual scenario management is shown in figure 13.

2003/2004 SIMULATION INFRASTRUCTURE

The aforementioned new capabilities are integrated into the simulation infrastructure as shown in figure 15, below. The new MACS based controller stations will directly interface with the ADRS simulation hub and host simulator, and no longer be part of the CTAS software suite. DCTAS tools will interface with the host and radar simulation, which provides a more field like infrastructure.

Most of the single pilot stations that previously combined the PcPlane with the CDTI will become combinations of MACS and CDTI. Multi aircraft MACS/CDTI stations can simulate many pro-active aircraft, thus generating a realistic environment for DAG-TM research. This capability will be exercised extensively for investigating concepts that require aircraft to be responsible for separating themselves from other aircraft. A high number and fidelity of these autonomous aircraft will allow us to investigate the scalability aspects of autonomous operations.

The weather server simulates a real-time weather feed. A simulation management console enables process and scenario configuration and monitoring.

The simulation environment will be connected to other simulation facilities. Currently work is underway to establish the connection to the Air Traffic Operations Laboratory (ATOL) at NASA Langley. In 2004 the Future Flight Central Tower simulation at NASA Ames Research Center will also be connected. Both simulation environments are implemented in a High Level Architecture (HLA) framework. The connection will be established via a gateway between the ADRS and the HLA environment. The next section shows the Ames/Langley connection as one example.

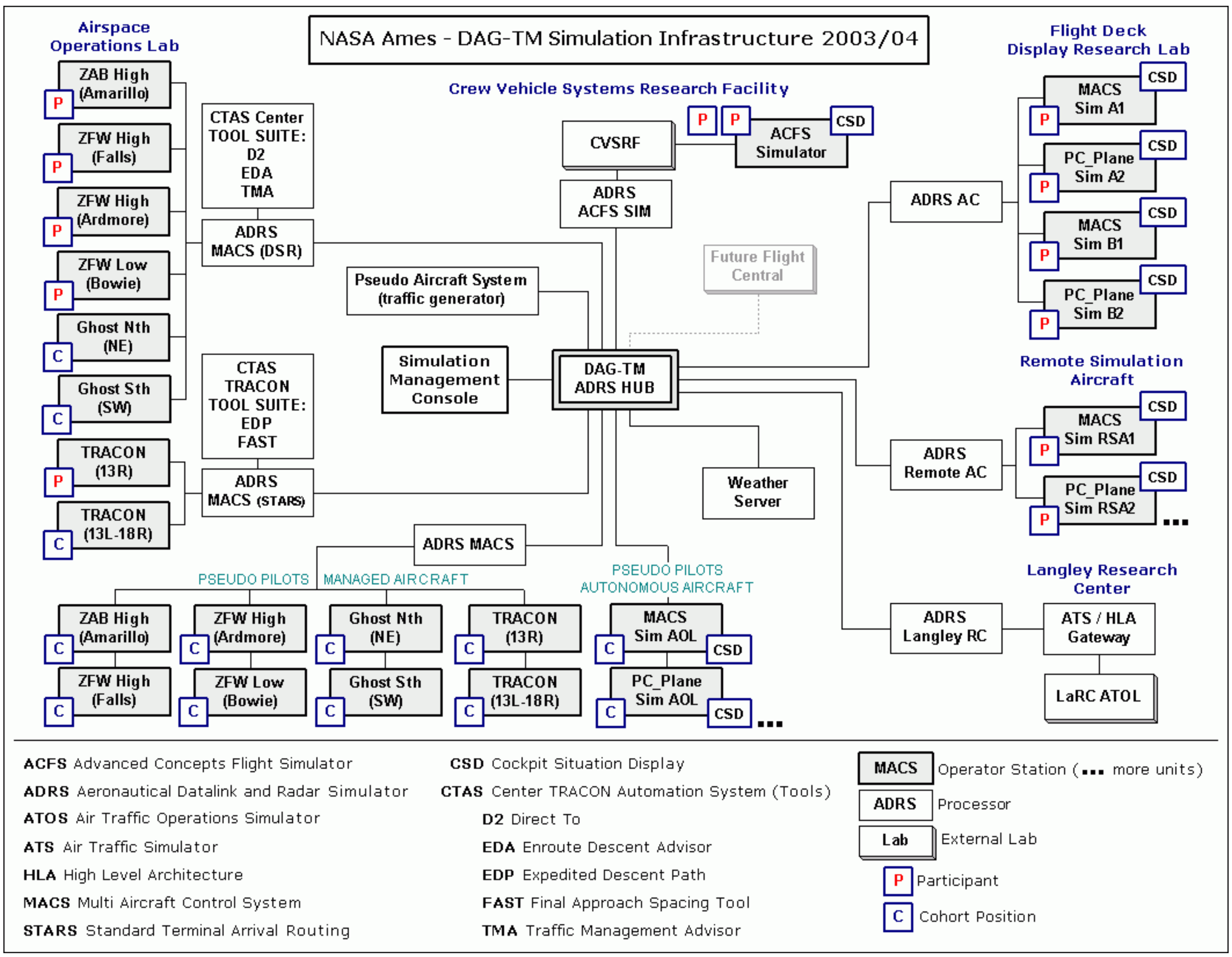

Figure 15. DAG-TM simulation infrastructure for 2003/04. Future Flight Central (supporting simulated tower operations) is a planned addition, but beyond the current time horizon

FURTHER EXPANSION

AMES CONNECTION TO LANGLEY'S ATOL

The Air Traffic Operations Laboratory (ATOL) is a mid-fidelity simulation facility under development to support research of air traffic operations within future airspace environments at NASA Langley Research Center.[12] It hosts the Air Traffic Operations Simulation (ATOS), a workstation-based human-in-the-loop simulation that serves as a test bed for investigations of future distributed air/ground traffic management concepts and their associated decision support tools.

An independent aircraft simulation, referred to as the Aircraft Simulation for Traffic Operations Research (ASTOR), is employed for each single pilot aircraft represented within ATOS. These workstation-based, HITL aircraft simulations have 6 degree of freedom dynamic models supported by actual aircraft aerodynamic data. The dynamics model can simulate jet and piston aircraft, and the simulation is equipped with representative cockpit displays and equipage levels for the different types of aircraft.

The ADRS-ATOS connection is established by a gateway process called Air Traffic Simulation Gateway (ATS_gateway). The architecture is indicated in figure 15. The "cross-country" connection between the two centers is established by connecting ADRS processes running locally at ARC and LaRC. An initial connectivity test was conducted in March 2003 and was very successful. Full connectivity including exchange of all messages to support DAG-TM operations between the two environments is expected to be established by September 2003.

MODEL-BASED AGENT SUPPORT

The DAG-TM simulation environment and MACS in particular, provides a high degree of flexibility and extensibility for including model-based agents in simulations. Agent-based simulations are already prevalent within the ATC/ATM research community. As detailed in Callantine, et al.,[11] DAG-TM simulation research can likewise benefit from agents operating with various levels of autonomy for a variety of purposes, from performing ATC and piloting tasks, to detecting operator errors, to generating performance metrics, to performing basic simulation-support tasks. For example, MACS-based agents that function as air traffic controllers can reduce costs and improve consistency by standing in for confederate controllers in human-in-the-loop studies. Further, agents can support studies of operations in a specific sector under a wide variety of conditions. Agents that represent pilots can further streamline ATC studies. All of these applications maintain a close correspondence with the full DAG-TM simulation environment, sharing the same airspace, traffic, interfaces, and automation tools. In addition, fast-time agent-based simulations can cover a broad range of experimental conditions inexpensively, helping to identify those that are likely to reveal important performance differences in full-scale simulations.[10]

Many agent applications are under development, some are planned for use in 2003 DAG-TM simulations. For example, MACS-based agents handle a variety of pseudo-pilot functions, such as handoffs and frequency transfers. More advanced ATC agents that can for example set up traffic flows for participant controllers autonomously are planned to be integrated in 2004.

CONCLUDING REMARKS

Realistic human-in-the-loop simulations of DAG/TM concepts require participation of numerous pilots, controllers, airline dispatchers, researchers and the operational community alike in order to gain a solid understanding of interactions in the very complex distributed air traffic environment. A simulation infrastructure was created at NASA Ames Research Center that covers many requirements for appropriate fidelity levels. The initial environment has been successfully used in research studies and demonstrations. Shortcomings have been determined and the identified upgrades are currently phased into the simulation architecture. With these modifications in place and the real-time connection to other facilities and laboratories the simulation environment provides a highly realistic and flexible test bed for advanced air traffic concepts.

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